

Sensorless Explicit Model Predictive Control for Multi-phase Buck Converters with Variable Output Voltage

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Abstract — The purpose of this paper is to use the predictive control to take advantage of the future information in order to improve the reference tracking. The control attempts to increase the bandwidth of the conventional regulators by using the future information of the reference, which is supposed to be known in advance. A method for designing a controller is also proposed. A comparison in simulation with a conventional regulator is made controlling a four-phase Buck converter. Advantages and disadvantages are analyzed based on simulation results.

I. INTRODUCTION

In the last years, an increasing number of papers have been published on the use of Model Predictive Control (MPC) for power converters [1]-[4]. Most of them focus on using this technique to handle nonlinearities and constraints of the converter, thus to optimize the control law for several conduction modes. In this paper we are more interested on the possibilities offered by this type of control for output reference tracking, when a future knowledge of the reference is provided.

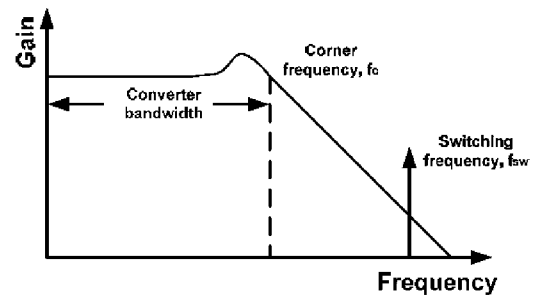
There are several applications in power electronics where a variable output voltage reference of a DC/DC converter is known in advance. Examples may be Radio Frequency (RF) transmitters when the Envelope Elimination and Restoration (EER) or the Envelope Tracking (ET) techniques are applied to cut down the losses in the RF amplifier. In both cases the supply voltage of the transmitter amplifier is changed in order to follow the envelope of the amplified signal. A delay of just a few control intervals between the amplified signal and the envelope is equivalent to providing the controller of the DC/DC converter with the future reference information.

The objective of this work is to evaluate which advantages in terms of reference tracking can be obtained by a digital controller based on MPC that uses the future information of the output reference, supposed to be known in advance. The goal is to design controller able to take advantage of the entire bandwidth of the converter, defined as in Fig.1 overcoming the limit of a conventional regulator. In fact, a fast design of a linear regulator presents a non-linear phase delay for reference frequency closed to the bandwidth of the regulator. Fig.2

equivalent to one third of the per-phase switching frequency of a four-phase Buck converter. Looking at the open-loop gain and closed-loop frequency response we can see that at the cross-over frequency the closed-loop gain is unitary but the phase delay is over 45° . It means that the regulator is only able to track a sinusoidal reference signal with a certain phase delay for frequency close to the regulator bandwidth.

So the idea of using a predictive control is to take advantage of future information of the reference to suppress this delay and so this would result virtually into a higher closed-loop bandwidth. The overall controller will be linear so it will have the same limit in bandwidth as a conventional regulator, but by using the future reference information it is expected to have a better tracking performance than a conventional regulator with the same bandwidth. In order to do it, at each control step the controller compares the future reference waveform with a prediction of the output voltage performed in open loop. A linear discrete-time model of the converter is used to obtain a prediction of the system state in a finite number of future control intervals. The prediction is compared with the future values of the reference and the error is properly weighed to determine the current value of the duty cycle. The design of the controller is performed off-line, by using Genetic Algorithm to select the optimum control gains.

In the next session the proposed approach is described. Consequently a design method for this solution is also suggested. Section IV provides simulation results of the controller and comparison with a conventional regulator. Conclusions and a prospectus for future work are outlined.



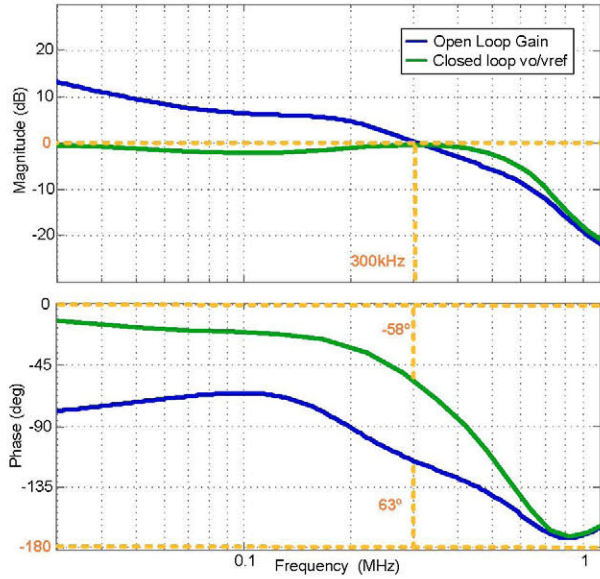
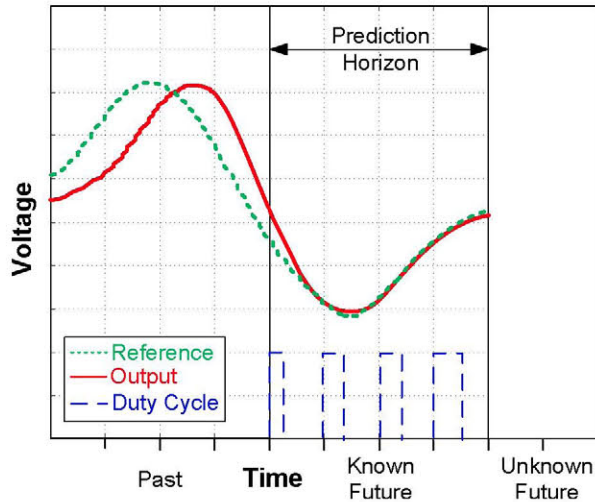


Fig. 2: Closed Loop and Open Loop Gain of a conventional regulator design

II. MPC: PROPOSED APPROACH

The MPC refers to a set of control strategies to optimize future control inputs on the basis of foreseen plant responses, Fig.3. At each control interval an MPC algorithm attempts to optimize future plant behavior by minimizing a proper cost function in a finite number of future control intervals, called prediction horizon (N). The first element of the optimum series of control values is applied to the plant, and the entire calculation is repeated at subsequent control intervals (receding horizon). In this way the algorithm introduces a feedback in the prediction that improves the robustness of the algorithm.

It is possible to distinguish between linear and nonlinear MPC. For linear MPC the prediction is performed by a linear time-invariant model and the minimization is performed off-line. For nonlinear MPC



any kind of model can be applied for the prediction and the minimization is performed in-line. In this work a linear discrete-time model will be used to describe the behavior of the system, so an *off-line* optimization of MPC will be performed in order not to increase the complexity of the control solution using a linear discrete-time model of the Buck converter.

In this case the cost function has to be quadratic, so for the reference tracking control problem the cost function is generally described as (1), whereas: the variable $e(k)$ represents the error in the future instants between the reference and the output voltage; $u(k)$ is the control variable, in this case the duty cycle, and Q and R are the weights respectively for the error and the control effort.

$$J(e(k), u(\cdot), k) = \sum_{i=0}^N [e(k+i)^T Q_i e(k+i) + u(k+i)^T R_i u(k+i)]$$

(1)

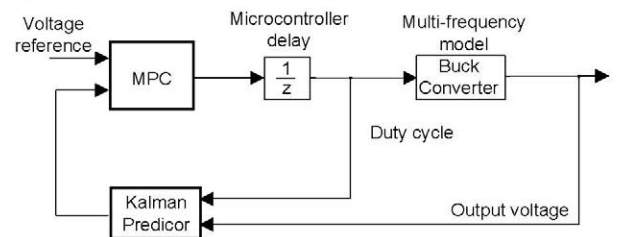
Since the purpose is to take advantage of future information to track variable signals, there is no need for using an integral action. An integral action would complicate the control the overall system, and it would make more difficult to track high frequency reference signals.

Future output voltage is predicted in open loop (duty cycle equal to zero) by mean of discrete time linear averaged model [5] [6] of the converter. Future reference, generally assumed to be equal to the current one, is in this case known in advance, so that the next duty cycle can be set, taking into account the future error between reference and the predicted output voltage.

The overall controller, in Fig.4, is stabilized by adding a one-step Kalman predictor to compensate the internal delay of the controller.

III. DESIGN METHOD

The key point for a good tracking using such a control is to get a good balance between the weight of the predicted error and the weight of the actual error, in order to prevent anticipating too much control action or to delay it. For this reason, the choice of the weights R and Q has not been conducted manually but a search algorithm based on Genetic Algorithm (GA) [7] has been



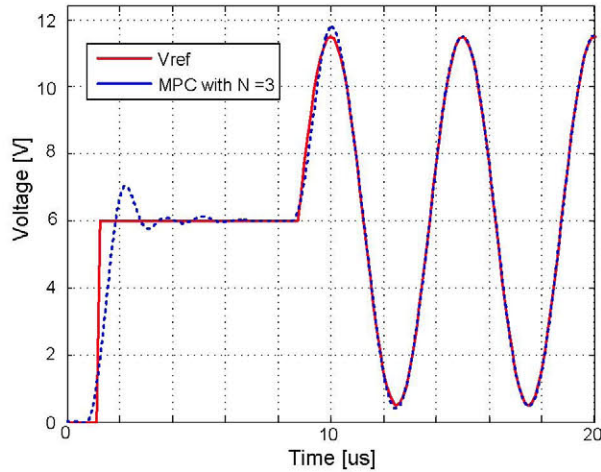


Fig.5: Characteristic of the chosen reference for weight optimization

applied to choose control gains.

Starting from a random set of gains, the GA assigns a fitness value to each of them. Such a value is a measurement of how good is the control to track the reference signal. In order to evaluate the fitness, the algorithm evaluates the response of the closed loop system when a certain set of weights is chosen for the controller, and the fitness for that particular set of gains is calculated as in (2). At this step, the simulation is performed using a multi-frequency model [8] of the Buck converter. Consequently the algorithm chooses a set of solutions with the best fitness, in this case the lowest the best, and by merging and modifying the best solutions the GA generates another generation of possible set of gains that will be expected to have better performance in terms of reference tracking.

$$\text{fitness} = \sum_t (y_{\text{ref}}(t) - y_{\text{out}}(t))^2 \quad (2)$$

So, in the attempt to minimize the fitness the GA is able to find an optimum set of weights to track a given reference. Depending on the application we could be more interested to track a certain type of waveform. In this case we are more interested in showing which advantages compared to a conventional type-three regulator we can obtain by using the available future information of the reference. Thus, the predictive controller has been designed in order to track a sinusoidal reference at the frequency of one tenth of the switching frequency.

On the other hand, being able to track perfectly a sine waveform can lead to a regulator close to the instability. In order to ensure the stability, a step function has been added to the waveform, as shown by Fig.4. In this way the finite response to the step function will guarantee the stability of the converter.

The design has been performed in Matlab/Simulink, where the Buck converter has been modeled by a time-

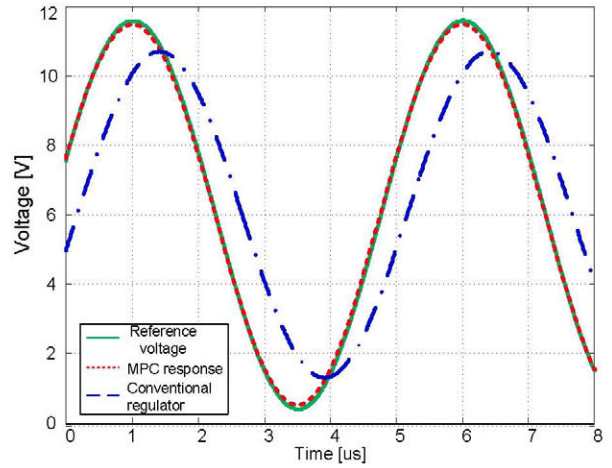


Fig.6: Comparison of the proposed approach with a conventional regulator in tracking a 200k Hz sinusoidal reference

notch filter is used to take into account the additional phase reduction of the system at frequency close to half of the switching one, due to the Pulse Width Modulation (PWM). This phase delay for a certain frequency is the higher the larger the closed-loop bandwidth. For this reason, the notch filter has been designed in order to have the same phase reduction of a system with a cross-over frequency equal to one third of the switching frequency, generally accepted as the highest bandwidth reachable by a linear controller.

IV. SIMULATION RESULTS

The solution has been tested in simulation with Matlab/Simulink on a four-phase Buck converter with: 400nF of equivalent output capacitor with 15.9 mOhm of ESR and 1.7 nH of ESL; per-phase inductor of 6.8 uH with an equivalent output inductor of 1.7uH; a resistive load of 2 Ohm; a constant input voltage at 12V; a switching frequency of 1 MHz. The output voltage can vary in all the range of output voltage from 0.5V to 11.5V. For the simulation test, the linear model of the Buck converter, in Fig.3 has been modified taking into account: limited number of digits for the ADC; limited resolution of digital regulator; output voltage ripple. The sampling frequency is set four times higher than the switching frequency.

In order to evaluate the performance of the control, a comparison with a conventional regulator has been conducted. Fig.2 shows the design of the conventional regulator chosen for the comparison. The cross-over frequency has been set at one third of the switching frequency, at 300kHz and with a phase margin of 63°, taking into account the delay reduction given due to the PWM [8]. Under this condition both conventional regulator and MPC with three-step prediction horizon have been tested and their tracking skills have been compared. Fig.6 shows the response of both regulators

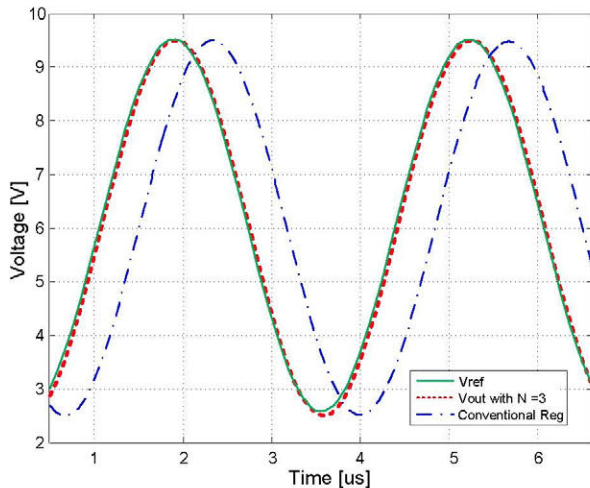


Fig.7: Comparison of the proposed approach with a conventional regulator in tracking a 300k Hz sinusoidal reference

200kHz, one fifth of the switching frequency. The simulation shows an interesting reduction of the phase delay at this frequency. The picture shows also a reduction of the magnitude for the conventional control that is not presented in the digital controller. This difference is not only due to the use of the reference information. In fact, the Kalman predictor is providing the controller with an estimation of the inductor current that is used for the open loop prediction. Thus, the model predictive control is somehow also controlling the inductor current, while only the output voltage is really measured.

The proposed approach shows also good reference tracking behavior for frequency of the reference signal higher than the bandwidth of the converter, as long as the output voltage range is consequently limited. Fig.7 shows that the conventional regulator is able to track a 300 kHz sinusoidal signal only with a delay of 30° , while the proposed approach does not show a significant delay.

V. CONCLUSION

The target of this work was to design a digital control for Buck converters, exploiting MPC theory and by taking advantage of the available future information of the reference in order to improve reference tracking. Simulation results show that the proposed solution, with a prediction horizon of three steps, is able to use this information to improve the performance of the conventional linear regulator. In case of sinusoidal waveform tracking, a reduction of 25° in the phase delay between reference and output has been achieved compared to a conventional linear regulator. A more significant reduction is achieved for frequency higher than the crossover frequency as long as the output voltage range is limited. The simulation took care of many characteristics as the limited number of digits for the

ADC, a limited resolution of the duty cycle due to the digital PWM. For this reason the results obtain in simulation should be obtained by future experimental results too. The good behavior shown by the proposed approach in simulation depends on the correctness of the converter parameters. For this reason, the future work will be to validate the robustness of the control system under possible variation of capacitor and inductors values as well as the output resistor is on schedule for future works. Another possible future work will be to apply the proposed approach to different converters, by simply adapting the design of the regulator to each particular case and we should expect to achieve similar results.

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